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Population structure and dynamics of *Prochilodus magdalenae* (Characiformes: Prochilodontidae) across migratory periods in the Sogamoso River basin (2014–2023)

Laura Cristina Garcia-Buchelly¹;  <https://orcid.org/0000-0001-8823-1097>

Jorge Luis Aristizabal Regino¹;  <https://orcid.org/0000-0001-7384-726X>

Samuel Restrepo Vélez¹;  <https://orcid.org/0009-0006-5264-6411>

Alejandro Betancur Henao¹;  <https://orcid.org/0009-0004-8967-7380>

Jonny Andrés Yepes-Blandón^{1*};  <https://orcid.org/0000-0001-6276-5488>

1. Grupo de Investigación en Organismos Acuáticos Nativos y Exóticos (GIOANE), Universidad de Antioquia, Medellín, Colombia; laura.garciab@udea.edu.co; jluis.aristizabal@udea.edu.co; samuel.restrepov@udea.edu.co; alejandro.betan-curh@udea.edu.co; jonny.yepes@udea.edu.co (*Correspondencia)

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ABSTRACT

Introduction: *Prochilodus magdalenae* (bocachico) is a key migratory species in the Magdalena River basin, with high ecological and fisheries relevance. However, its populations have declined due to overfishing and habitat degradation. This study analyzes the population dynamics of the bocachico in the Tienda Nueva - La Flor sector of the Sogamoso River during the period 2014–2023, evaluating its abundance, biomass, and relationship with environmental variables.

Objective: To characterize the population structure of *P. magdalenae* in the Tienda Nueva-La Flor sector of the Sogamoso River (2014–2023), identifying patterns of abundance, biomass, body condition, and their relationship with environmental factors.

Methods: A total of 47 770 individuals were analyzed from catches obtained between 2014–2023. Morphometric variables (total weight, total length, standard length), condition factor (K), and environmental parameters (flow rate, precipitation, temperature) were recorded. Statistical analyses included temporal trend evaluation, correlation analyses, and time-series modeling.

Results: A significant reduction in body size was detected, with a mean standard length (LS) of 20.85 cm and a predominance of individuals < mean size at capture (TMC) (25 cm LS) (81.7 %). Biomass exhibited interannual fluctuations, with peaks during the “main spawning migration” in most years. Abundance peaked in 2019, followed by a fluctuating trend in subsequent years. The length–weight relationship indicated negative allometric growth ($b = 1.864$), suggesting reduced weight gain relative to length. The condition factor varied significantly among years and migration periods, with lower values in 2015–2016 and an increase until 2021. Correlations between biological and environmental variables were generally weak.

Conclusions: The population structure of *P. magdalenae* has undergone significant changes in the last decade, with reduced average size and increased individuals < TMC (25 cm LS) captures. These findings suggest impacts of selective fishing and environmental variability. Management measures, such as minimum catch size regulations and continuous monitoring, are recommended to support the conservation of the species.

Key words: migratory fish; condition factor; fisheries management; flow rate; length-weight relationship.

RESUMEN

Estructura y dinámica poblacional de *Prochilodus magdalenae* (Characiformes: Prochilodontidae) durante migraciones, sector río Sogamoso (2014–2023)

Introducción: El bocachico *Prochilodus magdalenae* es una especie migratoria clave en la cuenca del río Magdalena, con alta relevancia ecológica y pesquera. Sin embargo, sus poblaciones han disminuido debido a la sobrepesca y la degradación del hábitat. Este estudio analiza la dinámica poblacional del bocachico en el sector Tienda Nueva - La Flor del río Sogamoso durante el periodo 2014-2023, evaluando su abundancia, biomasa y relación con variables ambientales.

Objetivo: Caracterizar la estructura poblacional de *P. magdalenae* en un sector del río Sogamoso, identificando patrones de abundancia, biomasa, condición corporal y su relación con factores ambientales.

Métodos: Se analizaron 47 770 individuos capturados entre 2014-2023. Se registraron variables morfológicas (peso total, longitud total, longitud estándar), factor de condición (K) y variables ambientales (caudal, precipitación, temperatura). Se aplicaron análisis estadísticos para evaluar tendencias temporales, correlaciones y modelado de series temporales.

Resultados: Se evidenció una reducción significativa en el tamaño de los individuos, con un largo estándar (LS) de 20.85 cm y un predominio de individuos < tamaño promedio de captura (TMC) (25 cm LS) (81.7 %). La biomasa total mostró fluctuaciones interanuales, con máximos en la “subienda principal” de la mayoría de los años. La mayor abundancia se registró en 2019, seguida de una tendencia fluctuante en años posteriores. La relación longitud-peso mostró un crecimiento alométrico negativo ($b = 1.864$), indicando una menor ganancia de peso en relación con la longitud. El factor de condición varió significativamente entre años y momento de migración, con valores más bajos en 2015-2016 y un incremento hasta 2021. La correlación entre variables ambientales y biológicas fue en su mayoría débil.

Conclusiones: La estructura poblacional de *P. magdalenae* ha cambiado en la última década, con reducción del tamaño promedio e incremento en la captura de individuos < TMC (25 cm LS). Estos cambios pueden estar asociados con la pesca selectiva y variaciones ambientales. Se recomienda implementar regulaciones sobre la talla mínima de captura y monitoreos continuos para evaluar el impacto ambiental en la especie.

Palabras clave: peces migratorios; factor de condición; manejo pesquero; caudal; relación longitud-peso.

INTRODUCTION

Prochilodus magdalenae (Steindachner, 1878), commonly known as bocachico, is a freshwater potamodromous fish endemic to Colombia, widely distributed throughout the Magdalena–Cauca basin and recognized as one of the country’s most important fishery resources (Mojica et al., 2012; Contreras-Almazo et al., 2019). Its life cycle is closely linked to fluvial connectivity and hydrological dynamics, which confer upon it a key role in both the sustainability of artisanal and commercial fisheries and the ecological functioning of continental aquatic ecosystems.

Within the Magdalena River basin, bocachico fulfills ecologically relevant functions. These include the recycling of organic matter, transfer of energy among habitats, and maintenance of ichthyic biodiversity.

Accordingly, it is considered an indicator species of the integrity and connectivity of tropical fluvial systems (Landínez-García et al., 2020; Escobar et al., 2021).

As a potamodromous species, *P. magdalenae* undertakes reproductive migrations influenced by flood and drought cycles. During low-water periods, individuals move toward spawning areas located both in the main channel of the Magdalena River and in its major tributaries, selecting sectors with hydrological and geomorphological conditions favorable for spawning. Subsequently, during high-water periods, they return to floodplain lakes (marshes), where feeding and growth phases take place (López-Casas et al., 2016; Doria-González et al., 2020; Roa-Cubillos & Villa-Navarro, 2019).

In recent decades, bocachico populations have experienced a marked decline in both abundance and fishery landings. Between 1974

and 1999, catches decreased by 70–80%, from ~80 000 to ~6 000 metric tons, a phenomenon primarily associated with overfishing, the loss of aquatic habitats, and reduced fluvial connectivity (Jaramillo-Villa & Jiménez-Segura, 2017; Mojica et al., 2012).

In parallel, a significant decrease in the mean standard length of the species has been documented, from values close to 38 cm in the 1970s to approximately 25 cm at present (Mojica et al., 2012; Roa-Cubillos & Villa-Navarro, 2019). This reduction in body size has important ecological implications, as it is associated with a younger age and smaller size at sexual maturity, a reduction in reproductive potential, and increased vulnerability of populations to fishing pressure, thereby compromising their long-term sustainability (Contreras-Almazo et al., 2019).

These population trends have led to *P. magdalenae* being classified under threat categories at the national level, initially as Critically Endangered and subsequently as Vulnerable, according to the *Libro Rojo de peces dulceacuícolas de Colombia* (Red Books of Colombian Freshwater Fishes) (Mojica et al., 2012). Nevertheless, at the global scale, the species was assessed by the International Union for Conservation of Nature (IUCN) in 2022 and categorized as “Data Deficient”, mainly due to the lack of recent and consistent information on abundance, population trends, and demographic structure across much of its distribution range (Sidlauskas & Valderrama, 2022). This discrepancy underscores the need for long-term regional studies that provide robust evidence on its population status.

The Sogamoso River, one of the main tributaries of the middle Magdalena River, plays a fundamental role in the migratory, reproductive, and population maintenance processes of *P. magdalenae*, functioning as a relevant fluvial corridor within the regional hydrographic network (Escobar et al., 2021). The recurrent presence of the species in this system, particularly during its migratory periods, makes it a strategic setting for monitoring

its population dynamics in relation to environmental variability.

Despite its ecological and fishery importance, knowledge of the population structure of *P. magdalenae* remains limited, particularly with regard to size composition, body condition, and interannual temporal variation in abundance. In this context, the present study aimed to characterize the population structure and dynamics of *P. magdalenae* in a sector of the Sogamoso River during a continuous ten-year monitoring period (2014–2023). To this end, species abundance, biomass, length–weight relationship, and condition factor were analyzed, as well as the relationships between these parameters and key environmental variables. The information generated seeks to contribute to the strengthening of evidence-based fisheries management and conservation strategies for fluvial systems of the middle Magdalena River basin.

MATERIALS AND METHODS

Study area: The Sogamoso River belongs to the Magdalena River basin and constitutes one of its main tributaries in the middle Magdalena region. It is formed by the confluence of the Suárez and Chicamocha rivers and flows for approximately 140 km before discharging into the Magdalena River, draining a basin of high ecological and fishery relevance for Northeastern Colombia (IDEAM, 2015; Mojica et al., 2012).

The Sogamoso River fluvial system is located at approximately 7°12'22" N, 73°55'17" W and traverses a mountainous landscape. This landscape is characterized by the presence of a canyon associated with the Serranía de la Paz, approximately 62 km downstream from the confluence of its formative rivers and about 75 km upstream from its mouth in the Magdalena River (Comisión Regional de Competitividad de Santander, 2014).

In the middle course of the Sogamoso River lies the Sogamoso Hydroelectric Power Plant (CH Hidrosogamoso), an infrastructure approximately 190 m high, with a 72 m-wide spillway and a reservoir of ~7 000 ha. This

structure causes longitudinal fragmentation of the fluvial system at an elevation of approximately 300 m a.s.l., constituting a relevant physical element within the regional hydrographic context (Comisión Regional de Competitividad de Santander, 2014; ISAGEN, 2016).

The study was conducted in a river stretch of approximately 3 km downstream from the dam, between the sectors of Tienda Nueva and La Flor, in the municipality of Betulia (Santander, Colombia) (Fig. 1). This river segment corresponds to a strategic point within the fluvial system, where the transit of fish is concentrated during reproductive migration periods. This sector exhibits a confined channel, with a predominance of rocky substrates and gravels, and a hydrological regime characterized by marked seasonal variability associated with the regional rainfall regime. River discharge in this stretch of the Sogamoso River also shows significant increases during high-water periods, directly influencing habitat availability and the

dynamics of migratory fishes (IDEAM, 2015; ISAGEN, 2016).

Data sources and collection procedures:

To evaluate the population dynamics of *P. magdalenae* between 2014 and 2023, this study was based on information collected during fish management activities conducted in the barrier zone by ISAGEN S.A. E.S.P. in the Sogamoso River, in compliance with the environmental license of the hydroelectric project. It is important to clarify that the analyzed data do not originate from systematic sampling, but rather from records obtained during fish capture, handling, and release activities conducted for environmental management purposes. As a result, sampling effort is neither constant nor standardized among years, periods, or operations, as it depends on operational, environmental, and logistical conditions specific to each management event.

The database used consists of 47 785 records corresponding to capture, measurement, and

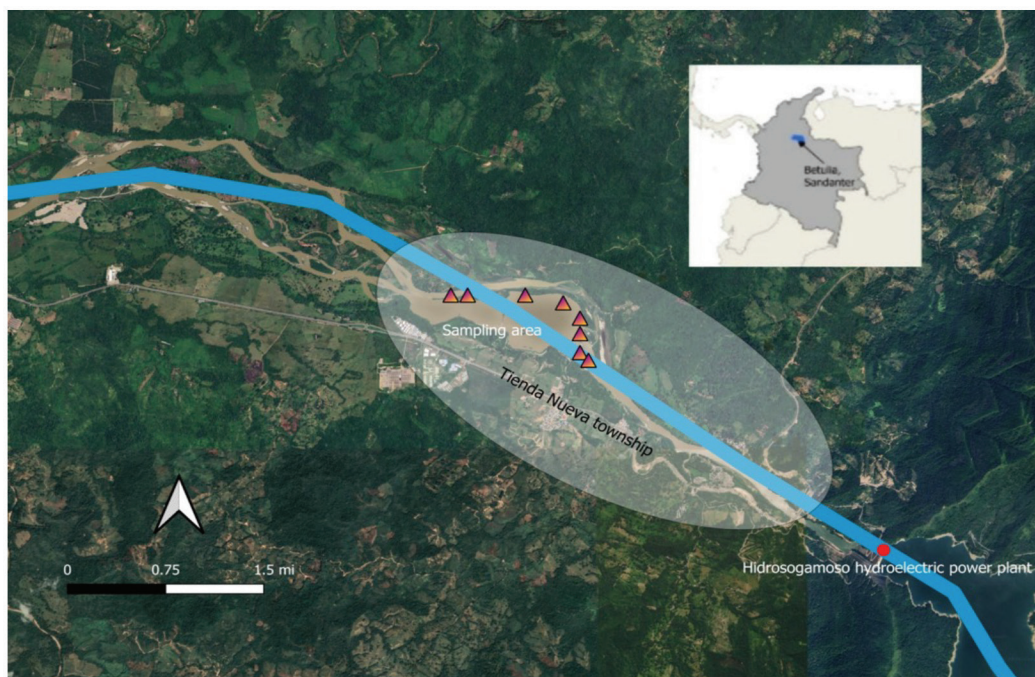


Fig. 1. Geographic location of the study area downstream from the Hidrosogamoso Dam, Sogamoso River basin, Santander (Colombia). Satellite image from Google Earth (© Google), 2023, modified by the authors.

release operations of specimens carried out in tributary streams of the Sogamoso River and/or in the reservoir. In accordance with the provisions established by the National Environmental Licensing Authority (ANLA, Ruling 0792 of 2014), fishing activities for management purposes were to be conducted mainly during the months of January, February, March, July, August, and December, or during months that coincided with the migratory movements of the species.

Collections were carried out in an artificial migratory barrier zone approximately 3 km long, located between kilometers 2 and 5 downstream from the dam, where a significant number of individuals concentrate during reproductive movements. Captures were conducted using 2, 3, and 4 point mesh cast nets, operated by artisanal fishers belonging to the ASOGAMOSO and ASOPERISO associations, from motorized canoes approximately 7.5 m in length.

Captured fish were initially placed in 60 L plastic tanks containing river water with continuous renewal and subsequently transferred to 1 000 L tanks with aeration, where handling procedures were performed. These included treatment with marine salt and activated carbon, as well as the gradual reduction of water temperature through the addition of ice. These actions were intended to minimize physiological stress and reduce mortality during the collection of biometric data, prior to the release of individuals back into the aquatic system.

During management activities, biometric variables were recorded for captured specimens, including total length (TL, cm), standard length (LS, cm), and total weight (WT, g). Environmental variables associated with each event were also documented, such as river discharge (m^3/s), precipitation (mm), and ambient temperature ($^{\circ}\text{C}$). Temperature was measured using a thermometer, precipitation data were obtained from a rain gauge station operating in the area, and discharge was based on hydrological information provided by the hydroelectric power plant.

Over the course of the study period, differences were observed in the intensity and temporal coverage of management operations. In particular, 2014 corresponded to an initial exploratory phase, with a lower number of operations and no records during the first half of the year; consequently, the available information for that year is restricted to the *Mitaca* (secondary migratory period) period (July–September) and the *Movimiento Final* (final migratory movement) period (October–December). In subsequent years, the frequency of management activities increased, and the temporal coverage of records expanded, allowing for more continuous information across the different migratory periods.

To facilitate temporal analyses, records were grouped into migratory periods based on the month of capture of each individual: *Subienda principal* (major upstream migratory period) (December–March), *Bajanza* (downstream migratory period) (April–June), *Mitaca* (July–September), and *Movimiento Final* (October–December), assuming a standard hydrological pattern. Differences in sampling effort and temporal coverage among years should be considered when interpreting inter-annual comparisons.

Condition factor (fish well-being status):

The body condition of individuals, understood as a reflection of their overall physiological status and the influence of internal and external factors, was evaluated using Fulton's condition factor (K) (Ricker, 1975). This index was calculated as:

$$K = 100 (WT / LT^3)$$

Where WT corresponds to the total wet weight of the fish (g) and TL to total length (cm). Fulton's condition factor allows for the assessment of temporal variations in the relative body condition of individuals and is widely used as a proxy for nutritional status and energy reserves, as well as for the overall degree of fish well-being across different developmental stages, seasons, or years (Lorencio, 1996;



Cala et al., 1996). High K values are generally associated with individuals exhibiting greater energy reserves, better nutritional condition, and favorable environmental settings, whereas low K values may reflect physiological stress, prolonged fasting, high energetic investment in reproduction, or limiting environmental conditions (Le Cren, 1951; Weatherley & Gill, 1987; Froese, 2006). In potamodromous migratory species such as *P. magdalenae*, temporal variations in the condition factor have been associated with reproductive cycles and migratory movements, during which individuals reduce food intake and mobilize energy reserves toward gonadal maturation and migration (Agostinho et al., 2004).

In this study, the condition factor K was analyzed comparatively among years and across the different migratory periods to evaluate temporal variations in the population's body condition. Given that the length–weight relationship exhibited allometric growth ($b \neq 3$), K values were interpreted solely in a temporal comparative context within the population, and not as an absolute measure of body condition among individuals of different sizes, following the recommendations of Froese (2006).

Length–weight relationship: The length–weight relationship (RLP) was estimated using a power regression that relates a linear measure (length) to a volumetric measure (weight) and describes the pattern of somatic growth in fishes (Ricker, 1975; Gulland, 1983; Pauly, 1984). This relationship is expressed by the equation:

$$WT = a \cdot LS^b$$

Where WT corresponds to the total weight of the fish (g), LS to standard length (cm), a is the regression intercept associated with body shape, and b is the growth coefficient. The value of parameter b allows the type of growth of the population to be assessed, being isometric when $b = 3$ and allometric when $b \neq 3$. This coefficient provides information on changes in body shape and energy allocation to growth throughout ontogenetic development

and constitutes a widely used tool to identify patterns of somatic growth and to evaluate population responses to environmental, trophic, and ecological variation over time. Although temporal variations in the length–weight relationship were explored, coefficient b was not formally compared among years or migratory periods; rather, its use focused on providing an interpretative framework for body condition analyses and on characterizing the overall growth pattern of the population during the study period.

Population structure: Population structure was analyzed based on the number of individuals captured per year, temporal variation in standard length (LS) and total weight (WT), and the classification of individuals (stage) according to an operational criterion based on the mean size at capture (TMC) established for the species in the Magdalena River basin (25 cm LS; Autoridad Nacional de Acuicultura y Pesca [AUNAP], 2018). Accordingly, individuals were grouped as < TMC (< 25 cm LS) and $\geq$ TMC ($\geq$ 25 cm LS). It is important to clarify that this classification does not correspond to a direct determination of reproductive status, as the study did not include gonadal analyses or the assessment of sexual maturity stages. Therefore, the defined groups should be interpreted solely as operational categories based on a fisheries management regulatory threshold, and not as juveniles and adults in a strict biological sense. This analysis allowed the identification of trends and patterns in population dynamics as the species reached the barrier zone during migration. Size and weight composition of the catch were used to calculate the annual and interannual (2014–2023) TMC and mean weight at capture (PMC), grouping data into 2-cm and gram intervals, following the methodology of Sparre and Venema (1997).

Data analysis: All statistical analyses were performed using RStudio software (R Core Team, 2023). Data processing and analyses were conducted using functions from the base stats package (R Core Team, 2023), as well as the

forecast (Hyndman & Khandakar, 2008) and ggplot2 (Wickham, 2016) packages.

Data screening and preparation: Prior to analyses, total weight (WT) data were screened by evaluating their biological consistency with standard length (LS). A total of 15 records with weight values incompatible with individual size, attributable to measurement or data-entry errors, were identified and excluded, as they generated extreme outliers in the condition factor. No extreme values were removed based solely on statistical criteria. Data normality and homoscedasticity were assessed using the Kolmogorov–Smirnov and Levene’s tests, respectively. Based on the fulfillment of statistical assumptions, parametric or non-parametric tests were selected for subsequent analyses.

Biomass analysis and individual records: Individual weight was used as a proxy for individual biomass, as it represents a direct measure of the amount of organic matter per specimen. Biomass comparisons were conducted among years and across migratory periods, considering the observational nature of the data and the lack of standardized sampling effort. When data met normality assumptions, a one-way ANOVA was applied, followed by Tukey’s post hoc test. In cases where data did not conform to a normal distribution, non-parametric tests were used, applying the Kruskal–Wallis test and Dunn’s post hoc test for group comparisons. In all cases, a significance level of $\alpha = 0.05$ was adopted. Additionally, records of the number of individuals per year and per migratory period were analyzed as a descriptive measure of temporal variation in capture events. Given that sampling effort was neither constant nor standardized among years or operations, standardized abundance metrics such as catch per unit effort (CPUE) were not estimated; therefore, results were interpreted comparatively and with caution.

Environmental correlation analysis: To explore environmental factors potentially associated with variations in body structure and

physiological condition of the population, a Spearman correlation matrix was constructed between environmental variables (river discharge, precipitation, and ambient temperature) and biological variables (LS, WT, and condition factor, K). Environmental variables (discharge, precipitation, and ambient temperature) were analyzed with a six-month time lag to represent the cumulative effect of prior hydrological and thermal conditions on somatic growth and body condition of individuals, in accordance with the bioenergetic dynamics of migratory fishes. Spearman correlation coefficients (r_s) were interpreted jointly with their levels of statistical significance (p) and sample size, following the criteria proposed by Pauly (1983). In this way, the strength and relevance of associations were evaluated based on their actual statistical significance, avoiding interpretations based solely on the magnitude of the correlation coefficient. This analysis aimed to identify how habitat conditions influence, with a temporal lag, the body structure and physiological status of the migratory population and was addressed as an exploratory and complementary component, oriented toward identifying potential associations between environmental conditions and population parameters, without establishing direct causal relationships.

Temporal projection analysis: Based on annual capture records, a time-series analysis was conducted using ARIMA (AutoRegressive Integrated Moving Average) models to project the relative occurrence of individuals in the study area for the period 2024–2026. Before model fitting, the stationarity of the time series was evaluated, and the necessary transformations were applied to meet this assumption. Model parameter selection (p , d , q) was based on information criteria, primarily the Akaike Information Criterion (AIC), prioritizing the most parsimonious models. The resulting projections should be interpreted with caution, as ecological time series often exhibit high interannual variability and are influenced by environmental and anthropogenic factors not explicitly included in the model.



Information corresponding to 2014 was included using a descriptive and exploratory approach, with the aim of documenting the presence of the species and providing temporal context to the analysis. Given that records for that year do not cover the entire annual cycle and correspond to a smaller number of management operations, their results should be interpreted cautiously and are not used as a primary reference for inferential temporal comparisons.

RESULTS

Temporal analysis of biomass and abundance: Analysis of total annual biomass by migratory period (Fig. 2A) revealed a general pattern in which the *Subienda principal* contributes the largest share of biomass in most of the evaluated years (2015, 2018, 2020–2023). However, exceptions to this pattern were observed: in 2016, the highest biomass was

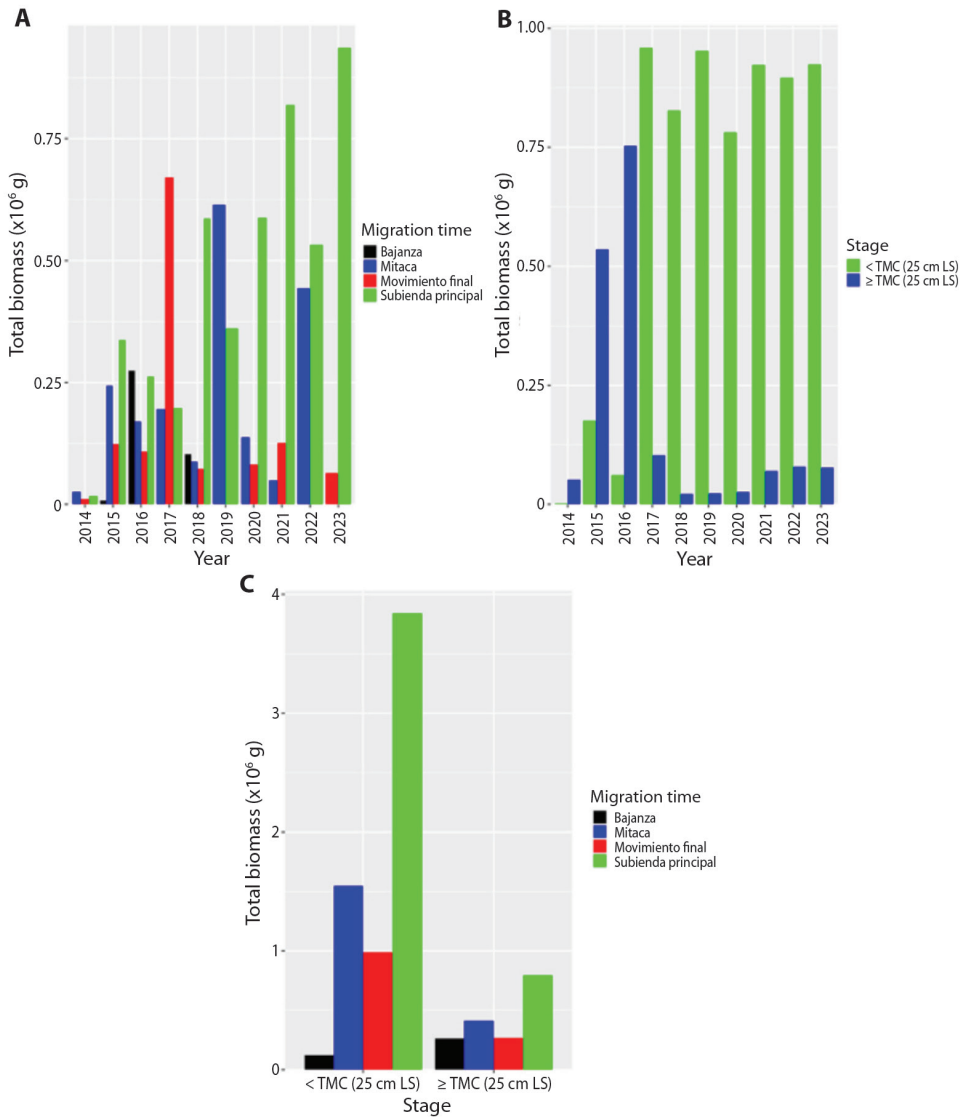


Fig. 2. A. Total biomass (g) by year and migratory period; **B.** Total biomass (g) by year and stage; **C.** Total biomass (g) by stage and migratory period.

recorded during *Bajanza*; in 2017 during the *Movimiento Final*; and in 2019 during *Mitaca*.

Significant differences in total weight were detected among migratory periods (Kruskal–Wallis: $H = 1627.8$, $p < 0.001$). Dunn's post hoc analysis with Bonferroni correction revealed significant differences among migratory periods, with *Mitaca* standing out as the period with the highest biomass values, in contrast to the *Movimiento Final*, which exhibited the lowest values.

These differences reflect contrasting patterns in fish biomass associated with the different migratory periods, which may be related to reproductive strategies, food availability, or hydrological characteristics specific to each period.

Analysis of total biomass across all years, disaggregated by stage (Fig. 2B), showed that individuals < TMC (25 cm LS) contributed a greater proportion of total biomass in most study years, except in 2014, 2015, and 2016. Similarly, biomass contributed by both stages was higher during the *Subiende principal*, with individuals < TMC (25 cm LS) maintaining the greatest overall contribution (Fig. 2C).

During the study period, a total of 47 770 individuals of *P. magdalenae* were recorded, with marked interannual variability in capture numbers across years and migratory periods (Fig. 3A). Overall, the *Subiende principal* concentrated the highest abundance values in most of the analyzed years, suggesting that this period represents the main pulse of individuals entering the barrier zone. However, specific exceptions were observed, such as in 2019, when the highest abundance occurred during *Mitaca*, and in 2017, during the *Movimiento Final*.

Abundance differed significantly among migratory periods ($p = 0.035$). Dunn's post hoc analysis with Bonferroni correction indicated that the only significant difference occurred between the *Subiende principal* and the *Movimiento Final* ($p_{adj} = 0.043$), while no statistical differences were detected among the other pairs of migratory periods.

When analyzing annual abundance by fish stage (Fig. 3B), a pattern similar to that observed

for biomass was evident. Individuals < TMC (25 cm LS) constituted the dominant fraction of total abundance in most years, except for 2014, 2015, and 2016. Consistently, when abundance was analyzed by stage and migratory period (Fig. 3C), the *Subiende principal* concentrated the highest number of individuals, including individuals < TMC (25 cm LS) that enter the barrier system together with the reproductive fraction of the population.

The reported abundance corresponds to absolute values derived from capture records during management activities; therefore, comparisons should be interpreted considering variations in sampling effort among years and periods.

Temporal analysis of the distribution of morphometric variables: total weight (WT) and standard length (LS). Table 1 presents the variation in length of the species over the study period (2014–2023). The minimum and maximum sizes were recorded in 2017 and 2016, respectively, with values ranging between 8 and 45 cm LS (20.86 ± 3.44 cm). Size structure exhibited a unimodal distribution with a peaking at ~20 cm LS, corresponding to the TMC. The size-frequency distribution showed an approximately normal shape, which was assessed graphically by overlaying a theoretical normal curve fitted to the observed data, following the approach proposed by Sparre & Venema (1997) (Fig. 4).

It should be noted that the number of individuals recorded in 2014 ($n = 202$) was considerably lower compared to subsequent years, representing less than 7 % of the annual average total. This difference in sample size should be considered when interpreting the results for that year. Table 2 presents annual variation in body weight over the study period (2014–2023), where the minimum and maximum values were recorded in 2019 and 2016, respectively, with values ranging between 9 and 953 g (mean $\pm$ DS: 172.59 ± 69.26 g), with a mean weight at capture of 172.59 g. Weight distribution was positively skewed, concentrated in low–intermediate ranges, with a right

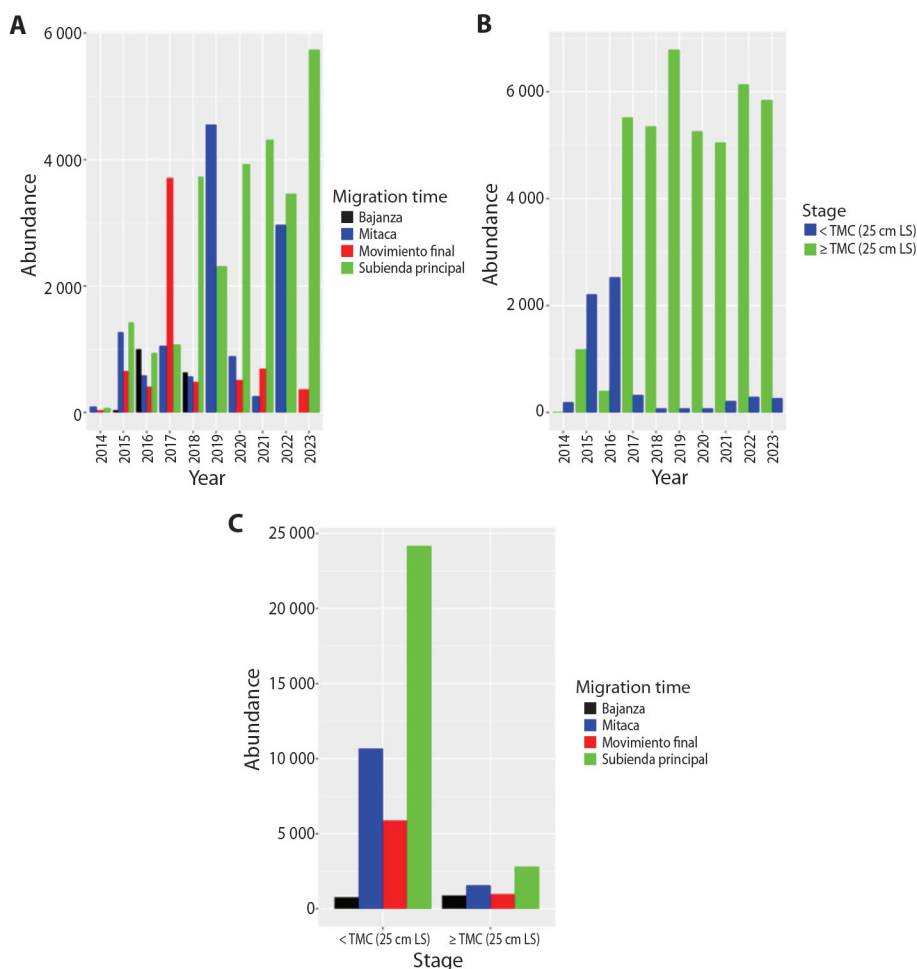


Fig. 3. A. Abundance by year and migratory period; B. Abundance by year and stage; C. Abundance by stage and migratory period.

tail reflecting larger individuals (Fig. 4). This pattern is characteristic of populations dominated by individuals < TMC (25 cm LS) and exhibiting high variability in body condition; consequently, total weight did not follow a normal distribution.

Determination of the condition factor (K): The condition factor (K) exhibited significant variation among the evaluated years (Fig. 5). Overall, K values showed an increasing trend throughout the study period, with a slight decrease in 2022. Multiple comparisons revealed groups of years with significant differences in body condition, with 2017 differing

markedly from 2014 and 2015 ($p < 0.001$). In contrast, no significant differences were observed between consecutive initial years, such as 2014–2015 and 2014–2016 ($p = 1.000$). Significant differences were also detected between 2018 and 2023, and between 2021 and 2023 ($p < 0.001$). These results reflect a progressive temporal variation in the population's body condition, consistent with interannual changes in population structure and environmental conditions of the system.

The condition factor (K) showed significant differences among migratory periods ($H = 1258.9$, $p < 0.001$) (Fig. 6). Overall, K values were highest during the *Movimiento Final*,

Table 1
Basic size information of bocachico (*Prochilodus magdalenae*) during the 2014–2023 period.

Year	n	Minimum (cm)	Maximum(cm)	DS	CV	IC_lower	IC_upper	TMC
2014	202	16.5	40.5	3.01	10.56	28.09	28.93	28.51
2015	3388	12.0	41.0	2.80	10.89	25.61	25.79	25.70
2016	2928	10.0	45.0	3.68	13.23	27.68	27.94	27.81
2017	5839	8.0	31.3	2.59	12.60	20.48	20.62	20.55
2018	5421	10.5	35.0	2.03	10.50	19.28	19.38	19.33
2019	6864	10.0	31.0	1.92	10.11	18.94	19.04	18.99
2020	5330	10.3	31.5	1.98	10.38	19.03	19.13	19.08
2021	5262	10.0	33.0	2.37	11.69	20.21	20.33	20.27
2022	6427	10.0	33.0	2.53	12.41	20.32	20.44	20.38
2023	6109	14.0	35.0	2.17	10.40	20.82	20.92	20.87
2014-2023	47770	8	45	3.44	16.5	20.82	20.88	20.85

n is the number of individuals, DS is the standard deviation, CV is the coefficient of variation, IC is the confidence interval, and TMC is the mean capture length.

Table 2
Basic information on weights of bocachico (*Prochilodus magdalenae*) during the period 2014–2023.

Year	n	Minimum (cm)	Maximum(cm)	DS	CV	IC_lower	IC_upper	PMC
2014	202	31.4	695	93.32	35.19	252.22	278.12	265.17
2015	3388	21.0	895	80.09	38.14	207.30	212.70	210.00
2016	2928	14.0	953	114.28	41.08	274.06	282.34	278.20
2017	5839	15.0	703	62.50	34.36	180.32	183.52	181.92
2018	5421	11.0	700	45.29	28.91	155.47	157.89	156.68
2019	6864	9.0	474	42.14	29.65	141.13	143.13	142.13
2020	5330	38.0	574	48.93	32.30	150.16	152.78	151.47
2021	5262	16.0	936	61.22	32.41	187.23	190.53	188.88
2022	6427	10.0	575	53.51	35.24	150.52	153.14	151.83
2023	6109	17.0	918	51.24	31.28	162.50	165.08	163.79
2014-2023	47770	9	953	69.26	40.13	171.97	173.21	172.59

PMC is the mean catch weight.

followed by *Mitaca* and the *Subienda principal*, while *Bajanza* exhibited the lowest values.

Comparisons among migratory periods indicated that the condition factor during *Bajanza* differed significantly from the *Subienda principal* (adjusted $p < 0.001$), but not from *Mitaca* (adjusted $p = 0.22$). In addition, no significant differences were observed between *Mitaca* and the *Movimiento Final* (adjusted p

$= 1.00$), nor between the *Movimiento Final* and the *Subienda principal* (adjusted $p = 1.00$).

The plots in Fig. 7 depict the condition factor (K) by migratory period over the ten years of the study, revealing clear fluctuations among the four migratory periods (Fig. 7B). Overall, marked differences among periods are observed, with notable variability across all years, including a minimum value of 0.65

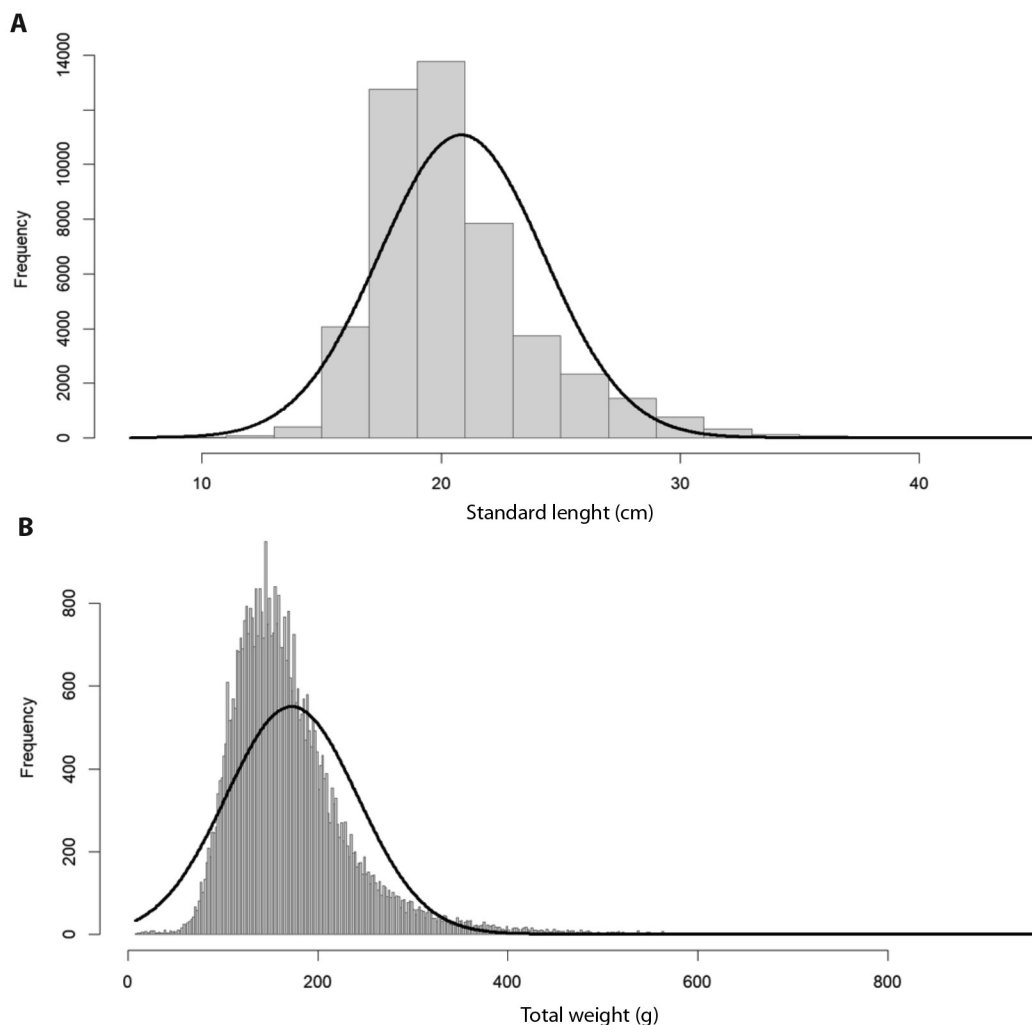


Fig. 4. Frequency distribution of standard length (LS) and total weight (WT) of bocachico (*P. magdalenae*). **A.** Length distribution. **B.** Weight distribution.

in 2016 and a maximum value of 1.19 in 2021 (Fig. 7A).

Length-weight relationship: The length-weight relationship showed negative allometric growth ($a = 0.569$; $b = 1.867$). The fitted model explained 66.43 % of the variation in total weight as a function of standard length ($R^2 = 0.664$), indicating a moderate fit. The slope of the model was statistically significant ($p < 0.001$). Residual analysis did not reveal

systematic patterns, suggesting that model assumptions were adequately met.

Fig. 8A shows the relationship between standard length (cm) and total weight (g) of *P. magdalenae*, together with the fitted allometric regression. Data dispersion around the regression line reflects individual variability in this relationship. In Fig. 8B, this relationship is presented disaggregated by year, showing that the growth pattern remains relatively constant throughout the study period, with only slight

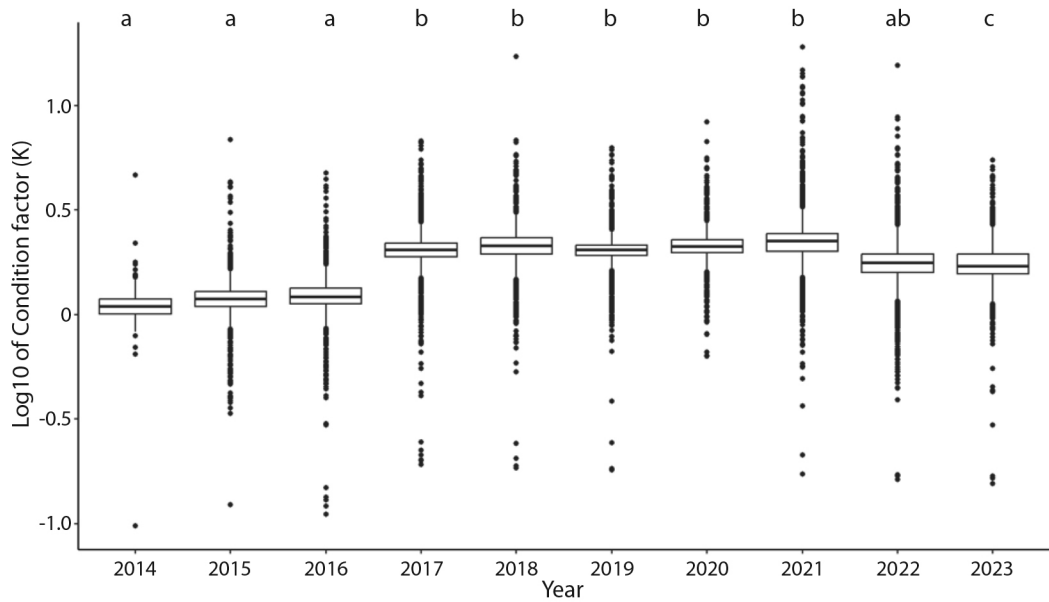


Fig. 5. Boxplot of the condition factor (K) distribution of bocachico (*P. magdalenae*) throughout the study period (2014–2023). Years that do not share the same letter show statistically significant differences, according to the Kruskal–Wallis test followed by Dunn’s post hoc test with Bonferroni correction ($p < 0.05$).

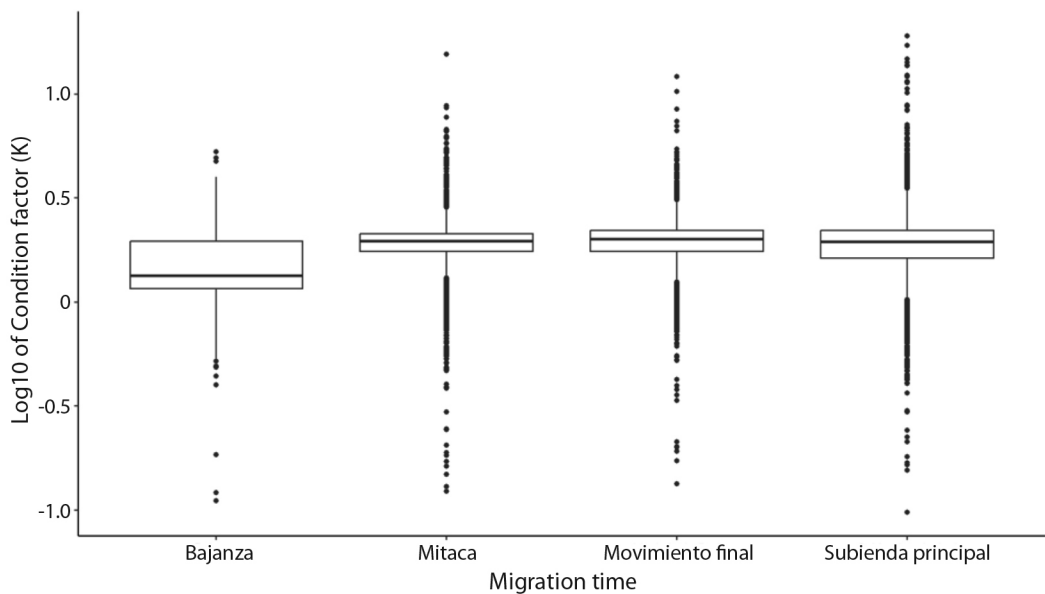


Fig. 6. Boxplot of the condition factor (K) distribution of bocachico (*P. magdalenae*) by migratory period.

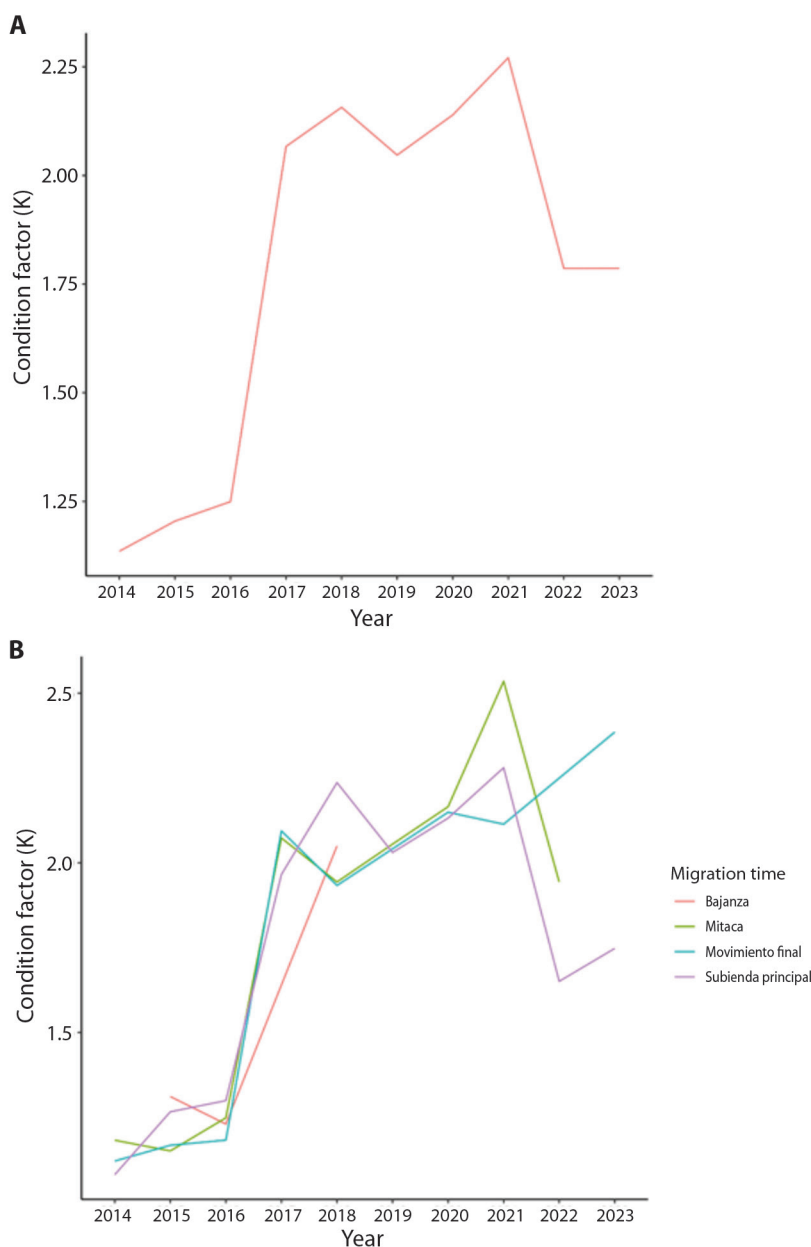


Fig. 7. Condition factor (K) of bocachico (*P. magdalenae*). **A.** Condition factor by year; **B.** Condition factor by year and migratory period.

variations in slopes. Statistical tests did not show significant differences in the allometric coefficient b among the analyzed years.

Correlation analysis: Fig. 9 shows the correlations between environmental and biological

variables of bocachico. WT correlated positively with LS ($r = 0.872$), while K correlated negatively with both WT ($r = -0.202$) and LS ($r = -0.524$). This pattern is consistent with the classical principle of the length–weight relationship, which establishes an inverse relationship

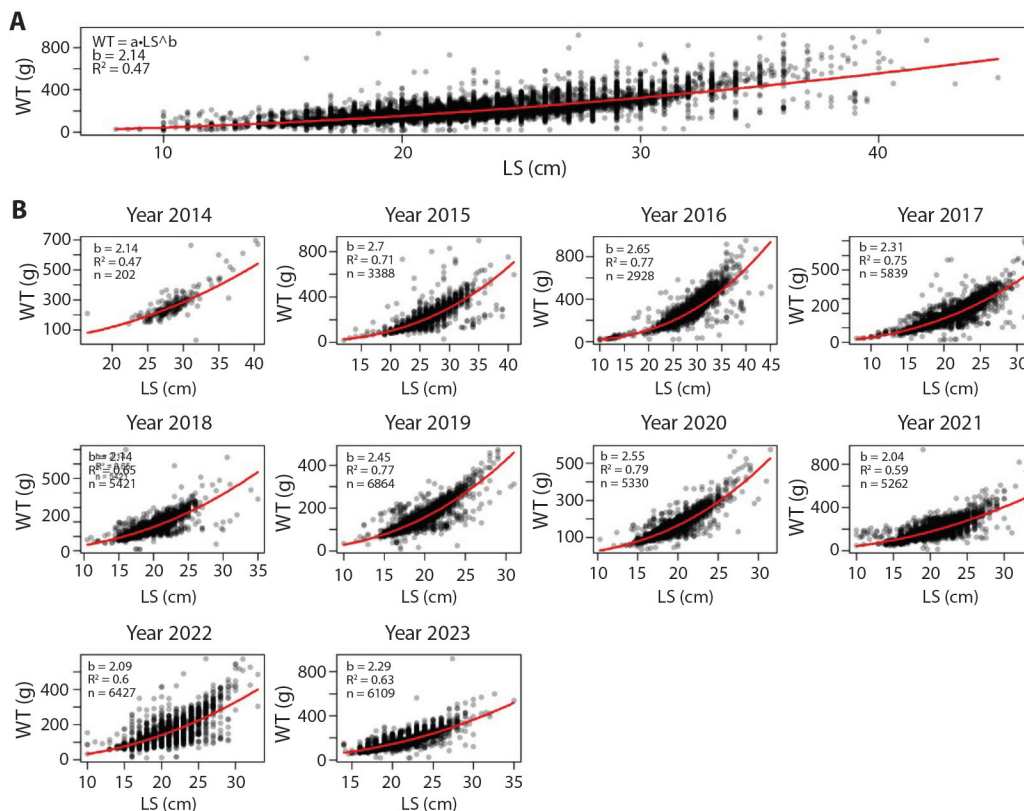


Fig. 8. Total length–total weight relationship of bocachico (*P. magdalenae*). **A.** Total length–total weight relationship during the 2014–2023 period. **B.** Length–weight relationship disaggregated by year.

between the allometric coefficient (b) and the condition factor (K). In this study, negative allometric growth ($b < 3$) explains why larger or heavier individuals exhibit relatively lower K values, regardless of the type of length considered or the associated environmental factors.

River discharge, evaluated with a six-month time lag, showed a positive correlation with the condition factor ($r = 0.347$), which is consistent with the role of antecedent hydrological regimes in habitat availability and trophic resource supply influencing the body condition of migratory fishes. Water temperature, also evaluated with a temporal lag, showed negative correlations with total weight (WT) and standard length (LS), and a positive correlation with the condition factor ($r = 0.106$). This pattern agrees with the well-documented effect of temperature on metabolic processes,

somatic growth, and natural mortality rate (M) in fishes, where thermal variation modulates energy allocation between growth and maintenance. Finally, precipitation showed a positive correlation with river discharge ($r = 0.254$) and a negative correlation with temperature ($r = -0.206$), reflecting the expected interaction between climatic and hydrological conditions of the system.

ARIMA time-series analysis: An ARIMA (0,1,0) model fitted to data from 2014–2023 was used to project the number of *Prochilodus magdalenae* individuals for 2024, 2025, and 2026. The model yielded a mean squared error (σ^2) of 2,768,226, with goodness-of-fit criteria of AIC = 161.04, AICc = 161.62, and BIC = 16.24.

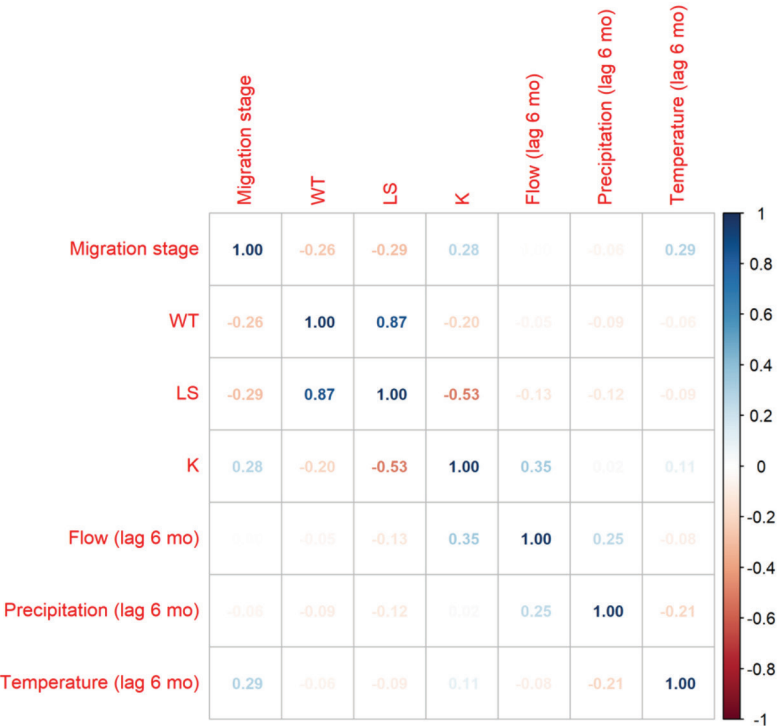


Fig. 9. Correlation matrix between recorded environmental variables and biological variables of bocachico (*P. magdalenae*) during the 2014–2023 period.

Point estimates for 2024, 2025, and 2026 were 6 109 individuals in each case. For 2024, the confidence intervals were 3 977–8 241 (80 %) and 2 848–9 370 (95 %). For 2025, confidence intervals ranged from 3 094 to 9 124 (80 %) and from 1 497 to 10 721 (95 %). For 2026, corresponding intervals were 2 416–9 802 (80 %) and 461–11 757 (95 %). The projections and their respective confidence intervals are presented in Fig. 10.

DISCUSSION

Population structure and temporal variability: During the study period (2014–2023), a total of 47 770 captures of *Prochilodus magdalenae* were documented, revealing marked interannual variability in the number of individuals, particularly between the initial years of the study (2014–2016) and the subsequent

period (2017–2023). In the early years, a maximum of 3 389 individuals was observed in 2015, whereas in later years captures showed a more uniform trend, with minimum values of 5 262 individuals in 2021 and maximum of 6 867 in 2019.

Results from the initial years, particularly 2014, should therefore be interpreted with caution, as this year presents a reduced sample size and limited temporal coverage, associated with the exploratory nature of management activities and differences in fishing effort. These conditions may introduce bias in comparative analyses; therefore, interannual trends are mainly supported by records obtained from 2017 onward, when greater temporal continuity and broader coverage of management activities were achieved. Nevertheless, after accounting for these methodological limitations, the observed variability in abundance

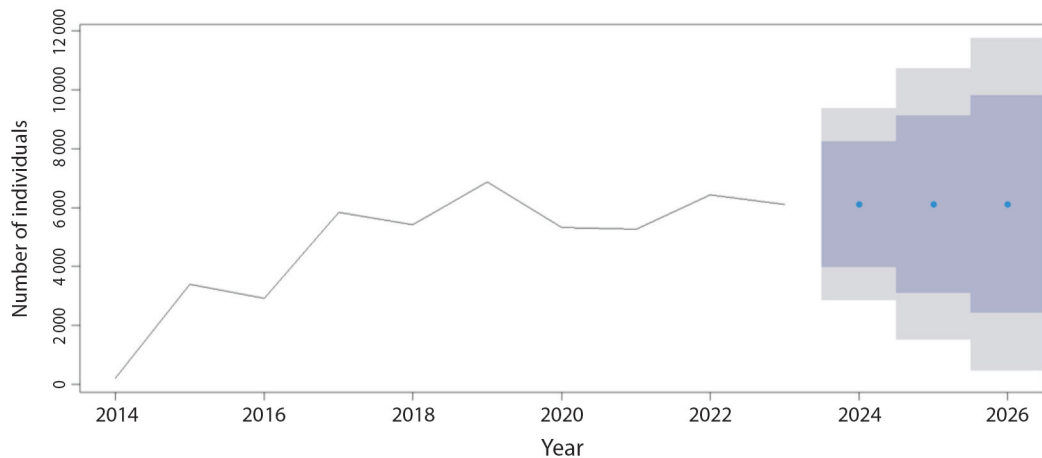


Fig. 10. Forecast of the number of *P. magdalenae* individuals based on the ARIMA (0,1,0) model. The line represents the historical values of the number of individuals recorded between 2014 and 2023. Blue dots correspond to point estimates for the years 2024, 2025, and 2026. Shaded areas indicate the 80 % (lighter shading) and 95 % (darker shading) confidence intervals.

and morphometric characteristics of bocachico largely reflects the population dynamics typical of rheophilic species of the order Characiformes, such as *P. magdalenae*, which are characterized by interannual fluctuations associated with migratory, hydrological, and environmental processes.

This species exhibits an r-selected reproductive strategy (sensu Taphorn, 1992), characterized by high fecundity, high mortality during early life stages, high adult survival, and strong natural fluctuations in population density (Taphorn, 1992). In this context, extreme climatic events associated with El Niño during the 2014–2016 period may have amplified these fluctuations by altering hydrological patterns of the Magdalena River and its floodplain, affecting reproduction, recruitment, and early survival processes of this migratory species (Castro Rubio, 2019; Fundación Humedales et al., 2016). These dynamics are consistent with the high variability documented in fishery landings in the Magdalena Basin, where the highest annual value occurred in 2017 (18 960 tons), exceeding that recorded in 2021 by 38.6 % (Duarte et al., 2022), reinforcing the notion of a population response highly dependent on interannual hydrological conditions.

Given that no significant correlation was observed between discharge and morphometric variables, it is not possible to infer that these factors indirectly affected population condition. The analysis by migratory period did not show significant differences in capture percentages overall, suggesting that interannual variability had a greater influence on population dynamics than seasonal fluctuations. Regarding stage distribution, the increase in captures from 2017 onward—associated with higher capture and transfer targets—was accompanied by a shift in the relative proportion of individuals $\geq$ TMC (25 cm LS) and individuals $<$ TMC (25 cm LS), with a progressive predominance of smaller individuals.

It is important to clarify that individuals $<$ TMC (25 cm LS) of *P. magdalenae* do not participate in reproductive migration; therefore, their presence in captures does not reflect migratory behavior but rather fishing selectivity processes. Consistent with this pattern, the intensive use of gillnets in the lower reaches of the Sogamoso River may favor the retention of larger individuals, allowing smaller fish to escape and continue upstream toward the dam site. This interpretation is supported by the observed size structure (Fig. 4), which shows



a high representation of sizes below the TMC and reinforces the effect of fishing gear on the recorded population composition.

Although reproductive migration of *P. magdalenae* mainly involves sexually mature individuals, the high proportion of individuals < TMC recorded in this study should not be interpreted as direct evidence of reproductive participation. Instead, this pattern reflects the size structure of individuals reaching the barrier zone, which is strongly influenced by fishing gear selectivity along the migratory route and by the absence of direct gonadal assessment.

The size range recorded in this study (8–45 cm LS) was broader than that reported for other water bodies in Colombia, where data are mainly derived from artisanal–commercial fisheries. Reported size ranges for other systems include 19–38 cm LS in the Atrato River and Tumaradó floodplain lakes (Jaramillo-Villa & Jiménez-Segura, 2017), 20–47 cm LS in the Marriaga floodplain lake (Roa-Cubillos & Villa-Navarro, 2019), 19.4–28.2 cm LS in the Sinú River Basin (Olaya-Nieto et al., 2017), and 15–34.5 cm LS in the San Jorge River (Doria-González et al., 2020), as well as 21.9–57.8 cm TL (Olaya-Nieto et al., 2021). Similar results were reported by Villalba-Quintero et al. (2019) for systems associated with the middle Magdalena River, where observed sizes reflect the direct influence of fishing gear selectivity and fishing pressure on population structure.

It should be noted that no historical data series are available for the analyzed stretch of the Sogamoso River that would allow long-term temporal comparisons within the same basin. Therefore, interpretation relies on comparisons with studies conducted in other regions of the Magdalena Basin and in tropical fluvial systems with similar ecological characteristics, an approach commonly used to contextualize population patterns in rheophilic migratory species without assuming undocumented historical scenarios.

The TMC recorded in this study (20 cm LS) was lower than that reported for the San Jorge River (TMC = 29.0 cm TL; Doria-González et al., 2020) and the Magdalena River (TMC = 22.8

cm TL; De la Hoz-M et al., 2009). Differences in size ranges and mean capture size among basins may be attributed to multiple factors, including sample size, sampling season, fishing gear type and selectivity, fishing pressure intensity, and environmental and hydrological conditions of each system (Segura-Guevara et al., 2011).

Considering the legal minimum capture size established for the species in the Magdalena Basin (25.0 cm LS), it was estimated that 86.9 % ($n = 41\,530$) of captured individuals were below this threshold and below the reported size at sexual maturity (MADR-CCI, 2007). This situation coincides with findings by De la Hoz-M et al. (2009), who reported a critical condition for *P. magdalenae* in the Magdalena River due to the high proportion of immature individuals in catches, exceeding 80 % in most cases. Similar results have been reported for the middle Magdalena River, where approximately 87 % of captures fall below the regulatory size (Arce et al., 2005), suggesting a scenario of growth overfishing with potential implications for population sustainability.

The sizes of *P. magdalenae* specimens captured in this study differ from those recorded in other basins, likely due to differences in fishing pressure, local population dynamics, and fishing gear selectivity along the migratory route. Decreases in mean fish size have been widely recognized as a population response to intense fishing pressure (Sparre & Venema, 1997; Welcomme, 1999; Allan et al., 2005), reflected in changes in size structure and in the proportion of mature individuals in catches. In this context, the smaller sizes recorded in the Tienda Nueva–La Flor sector may be associated with strong selectivity exerted by gillnets installed at the mouth of the Sogamoso River, where larger individuals are retained, allowing only smaller fish to continue upstream.

No direct analysis of reproductive status was conducted in this study, limiting precise inferences about gonadal maturity. However, in rheophilic fishes such as *P. magdalenae*, reproductive migration typically begins during low-water periods, when individuals show good body condition and early gonadal development

stages, using accumulated energy reserves to complete gonadal maturation prior to spawning during the rainy season (Taphorn, 1992). Previous studies in the Magdalena Basin have documented that more than 70 % of catches occur below TMC due to factors such as overfishing and habitat loss (Olaya-Nieto et al., 2003; AUNAP & Universidad del Magdalena, 2013), consistent with the findings of this study.

Institutional records from ISAGEN S.A. E.S.P. indicate high fishing pressure on the species at different stages of migration. Before leaving the floodplain lakes of the Magdalena, individuals must pass through nets and gillnets placed at outlet channels. This pressure intensifies in the final kilometers before reaching the Magdalena River, where more than 15 gillnets have been identified in the Sogamoso River (downstream of El Pedral). These practices capture and select much of the migrating biomass, resulting in predominantly smaller individuals reaching the dam site.

Total weight (WT) was concentrated between 134 and 256 g, with a mean of 172.59 g, indicating that most individuals correspond to < TMC (25 cm LS) with low to medium body weights. This is consistent with previous studies, such as Fundación Humedales et al. (2016), which reported an average weight of 130 g and a maximum of 305 g, and Jaramillo-Villa and Jiménez-Segura (2017), who documented a mean of 140 g and a maximum of 305 g in the Atrato River. In the present study, the maximum recorded weight was 953 g; however, the low proportion of individuals reaching high weights suggests that the population is under strong pressure, likely related to intensive fishing and adverse environmental conditions.

These results highlight the need for continued monitoring of the morphological characteristics of *P. magdalenae*, as they represent key indicators of population dynamics and the impacts of anthropogenic and environmental factors, particularly in migratory fishes. Bocachico performs long-distance reproductive migrations ranging from 200 to 500 km, from floodplain lakes to spawning areas, making it especially vulnerable to habitat fragmentation

and fishing pressure (Mojica et al., 2012; Jiménez-Segura et al., 2014).

Population condition and growth patterns: The Fulton condition factor (K) for *P. magdalenae* obtained in this study was 1.031 ± 0.282 , a value within the range reported for the species in other regions. For example, Contreras-Almazo et al. (2019) reported an average K of 1.22 ± 0.128 in the Zapatosa floodplain lake, while Jaramillo-Villa and Jiménez-Segura (2017) documented an average of 1.40 ± 0.2 in the Atrato River. Temporal fluctuations in K were observed, with lower values in 2015 and 2016, an increase from 2017 onward, and a slight decrease in 2022 during the main upstream migration. These variations suggest that body condition and physiological status may fluctuate over time, although they generally remained relatively stable during the last seven years.

Observed variations in condition factors may be associated with changes in food availability, energetic expenditure during migratory movements, and local environmental conditions, as reported for migratory species in tropical rivers. Reproductive migration involves high energetic costs, which may be reflected in temporary decreases in condition factor, particularly when coinciding with trophic limitations or hydrological alterations.

However, these results should be interpreted cautiously, as condition factor analysis may be influenced by size structure. In particular, a substantial proportion of individuals measured in 2015 and 2016 corresponded to $\geq$ TMC individuals, whereas < TMC individuals predominated in 2022. According to Froese (2006), robust comparisons require approximately similar numbers of small, medium, and large individuals selected at random; therefore, observed interannual differences may be partially biased by size composition. Despite these limitations, the temporal pattern provides relevant information on the physiological dynamics of *P. magdalenae* in a river stretch influenced by a hydraulic barrier.



Although a size-stratified analysis of condition factor would allow more precise separation of physiological variation from population structure effects, this approach was not implemented due to the nature of the data, which originate from management activities with variable capture effort rather than systematic sampling. Consequently, observed differences in K should be interpreted primarily as comparative temporal indicators at the population level rather than as absolute estimates by size class.

The growth coefficient of the length-weight relationship ($b = 1.864$) estimated in this study was lower than values reported for other Prochilodontidae species in South America, which generally range from 2.84 to 3.38 (Barbieri & Cestaroli, 2000; Olaya-Nieto et al., 2003; De La Hoz et al., 2009; De Oliveira Nuñez & Zaniboni-Filho, 2009; Oliva-Paterna et al., 2009; Vicentin et al., 2012; Llamazares Vegh et al., 2014; Nobile et al., 2015; Cella-Ribeiro et al., 2015; Silva & Stewart, 2017; Villalba-Quintero et al., 2019). Similarly, it was lower than values reported for *P. magdalenae* in other Colombian basins, where b ranges from 2.84 to 3.42 (Restrepo-Montoya, 2001; Jaramillo-Villa & Jiménez-Segura, 2017; Olaya-Nieto et al., 2021). Negative allometric growth ($b < 3$) is characteristic of early developmental stages, where fish prioritize length increase over proportional weight gain. However, the particularly low value recorded here suggests the influence of specific ecological and demographic conditions. The inclusion of a wide size range, prolonged and continuous sampling, and data collected during different migratory moments allow this coefficient to be interpreted as an integrated signal of fishing pressure along the migratory route and potential energetic constraints associated with hydrological alteration.

In rheophilic fishes such as *P. magdalenae*, low b values have been associated with reduced somatic growth in weight relative to length, reflecting environmental stress, high competition, or intense exploitation. Thus, the estimated b value provides additional evidence of the population status of *P. magdalenae*

in the Sogamoso River and its connection with hydrological and fishing dynamics of the middle Magdalena.

This pattern may also be influenced by migratory habits, particularly trophic and reproductive strategies. Feeding primarily occurs in floodplains, where individuals accumulate energy reserves before initiating reproductive migration. Ramírez & Pinilla (2012) reported that a high proportion of bocachico captured in the Sogamoso River had empty stomachs (88.5 % vacuity), indicating low feeding activity during migration. During this period, individuals rely on stored energy to sustain metabolism, migration, and gradual gonadal maturation, which may be reflected in variations of condition factor. However, reduced feeding during migration does not directly explain low b values, which reflect integrated somatic growth patterns at the population level rather than transient physiological responses.

Impact (correlation) of environmental factors: A strong relationship was observed between total weight and length, consistent with biological expectations. However, condition factor showed weak relationships with total weight, suggesting that other factors influence body condition, particularly those associated with migratory condition during periods of lower rainfall and higher temperature. Correlations indicated general associations with these climatic variables, coinciding with periods of reduced discharge and active migration.

Overall, correlations between biological and environmental variables were weak, likely due to the interaction of multiple factors. Fishing gear selectivity downstream, particularly gillnets in the Magdalena River and at the Sogamoso River mouth, may influence the size structure of individuals reaching the study area, resulting predominantly in smaller individuals. Additionally, the regulated flow regime of the analyzed stretch may attenuate environmental signals, complicating detection of clear linear relationships.

It is important to emphasize that this study was not designed to evaluate hydrological

regulation effects or to establish causal relationships; therefore, observed patterns should be interpreted as the result of interactions between migratory biology, regional environmental variability, and local hydrological characteristics.

Finally, ARIMA (0,1,0) projections for 2024–2026 suggest stabilization of captures at approximately 6 109 individuals per year. Although this may indicate relative equilibrium in the number of migrants reaching the Sogamoso River, widening confidence intervals highlight uncertainty inherent in long-term ecological forecasts. Unpredictable factors such as ENSO events, improvements in fishing gear, floodplain drainage, and other anthropogenic activities could significantly alter these projections.

The high proportion of individuals < TMC (25 cm LS), low condition factor, and negative allometric growth indicate a vulnerable status of the migratory population of *P. magdalenae* in the Sogamoso River. Although hydrological pulses influence migration, anthropogenic factors such as intensive downstream fishing likely determine the observed population structure. Overall, these findings reinforce the need for continued monitoring and the promotion of sustainable management actions for conservation of the migratory population of *P. magdalenae* in the Sogamoso River.

Author contributions: Laura Cristina García-Buchelly contributed to study conception and design, data analysis, interpretation of results, and drafting and final revision of the manuscript. Jorge Luis Aristizábal Regino contributed to study conception and design, critical review, methodological adjustments, and preparation of the final version. Samuel Restrepo Vélez supported analysis, interpretation of results, and initial drafting. Alejandro Betancur Henao contributed to analysis, interpretation, and initial drafting. Jonny Andrés Yepes-Blandón coordinated the overall project, contributed to interpretation of results, and approved the final manuscript.

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